# Zero-point cooling and heating rate measurements of a single $^{88}Sr^+$ ion

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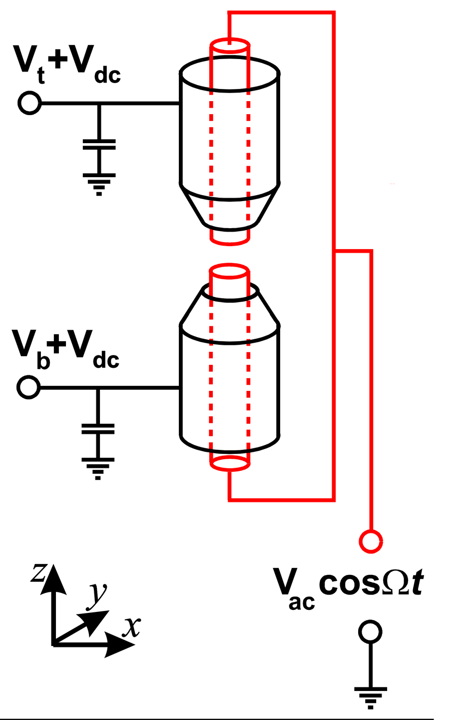
## Motivation

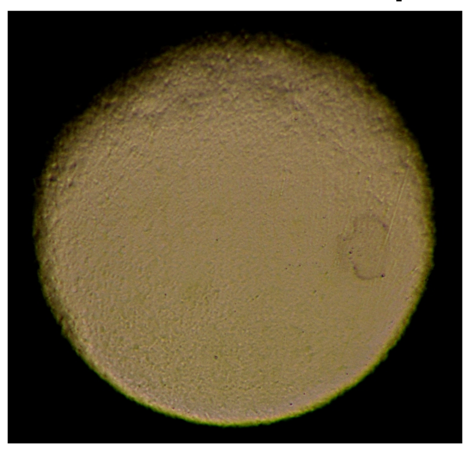
Strontium is a possible candidate for quantum information processing (QIP) due to the narrow $5s\,^2S_{1/2}$-$4d\,^2D_{5/2}$ electric quadrupole transition at 674 nm. The ideal starting point for efficient coherent manipulation of both internal and external degrees of freedom is an ion in the ground state of the trapping potential. This can be achieved by resolved sideband (RSB) cooling [1] in which the lower motional sideband of a narrow transition is driven.

We report the RSB cooling of a single $^{88}Sr^+$ ion in a radio-frequency endcap trap [2]. Our cooling scheme is similar to that demonstrated on the narrow optical $4s\,^2S_{1/2}$-$3d\,^2D_{5/2}$ transition in $^{40}Ca^+$ [3] where a quenching laser is used to adjust the scattering on the narrow transition to optimise the cooling rate.

The trap is configured to minimize the trapped ion's heating rate; specifically, improvements on the surface quality of the trap electrodes and ion loading using photo-ionisation of Sr atomic vapour [4] are employed. Following initial Doppler cooling on the 422 nm dipole transition to $\langle n_z\rangle = 8$ in the axial direction, 5 ms of RSB cooling reduces the ion's energy to $\langle n_z\rangle = 0.014(8)$ and a heating rate $d\langle n_z\rangle/dt = 0.05(1)$/ms is observed. These compare well to other values measured for traps of similar dimensions [5].

## The trap apparatus



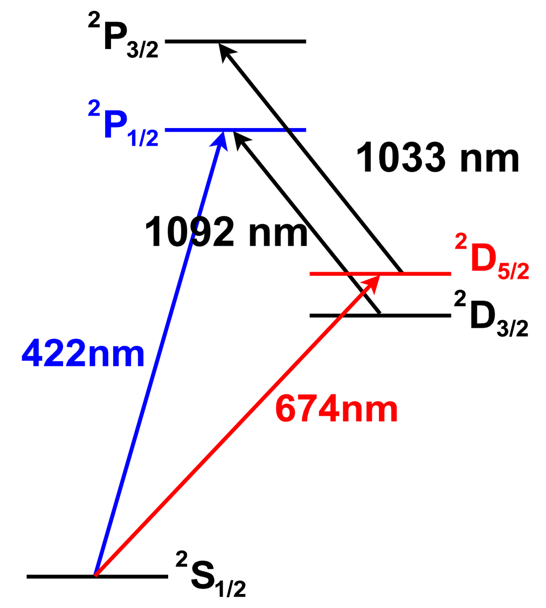



- helical resonator for RF
- / = 16.6 MHz
- $V_{ac}$ = 400 V
- $V_{dc}$ = 1.2 V (for motional sideband separation)
- / = 1.99 MHz
- / = 2.01 MHz
- / = 3.90 MHz
- inner endcap electrodes diameter 0.5 mm separation 0.56 mm
- outer endcap electrodes inner diameter 1 mm outer diameter 2 mm

endcap electrodes are made of tungsten wire with abrasively polished surfaces

- photo-ionisation loading to minimise contamination of trap environment [4]

## The $^{88}Sr^+$ ion and laser systems

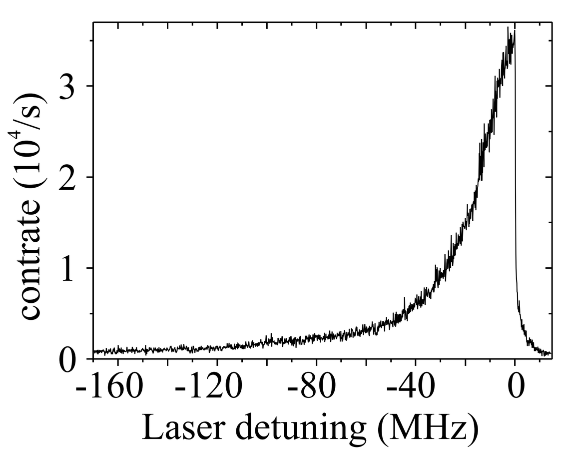



**422nm** dipole allowed transition ( /2 = 22 MHz) Doppler cooling, optical pumping, state detection
**674 nm** electric quadrupole transition ( = 391 ms) for spectroscopy
**1092 nm** repumping during Doppler cooling
**1033 nm** clearout after spectroscopy, quenching for RSB cooling

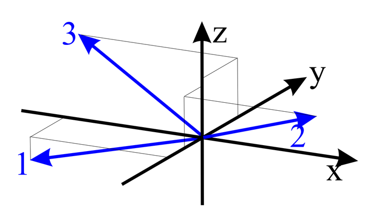
### Lasers [8]

**422 nm laser** IR-ECDL and $KNbO_3$ doubling-cavity, absolute frequency stabilisation to Rb-absorption line
**674 nm laser** Littman type ECDLs. **master**: FM-locked to high-Q ULE cavity( laser drift less than 2kHz/h, laser linewidth < 2kHz), **2 slave lasers:** sideband injection locked to master with 160 MHz variable offset.
**1092 nm laser** Littrow-type neodynium-doped fiber laser
**1033 nm laser** Littrow-type ECDL locked to a reference cavity
- mechanical shutters and AOMs are used for laser switching

## Detection and 3D micromotion compensation



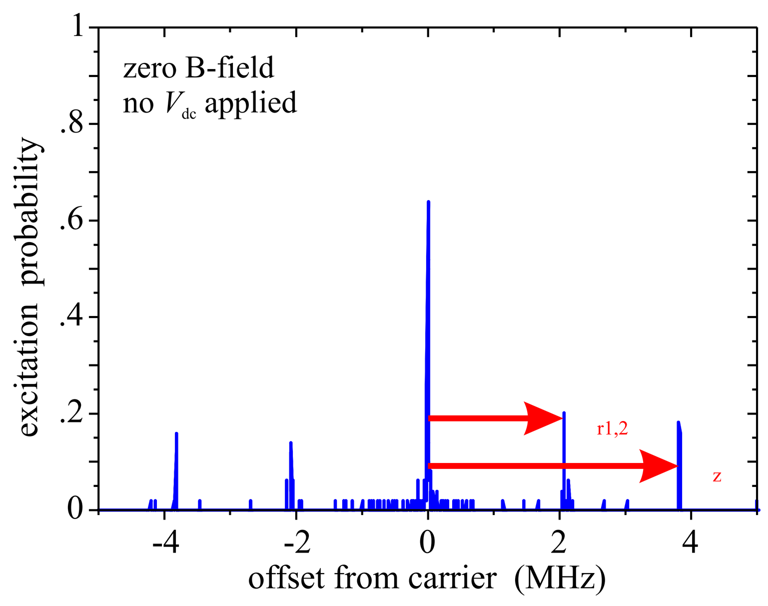

- 4 W @ 422 nm, into 50 m waist
- low background count rates
- high detection efficiency



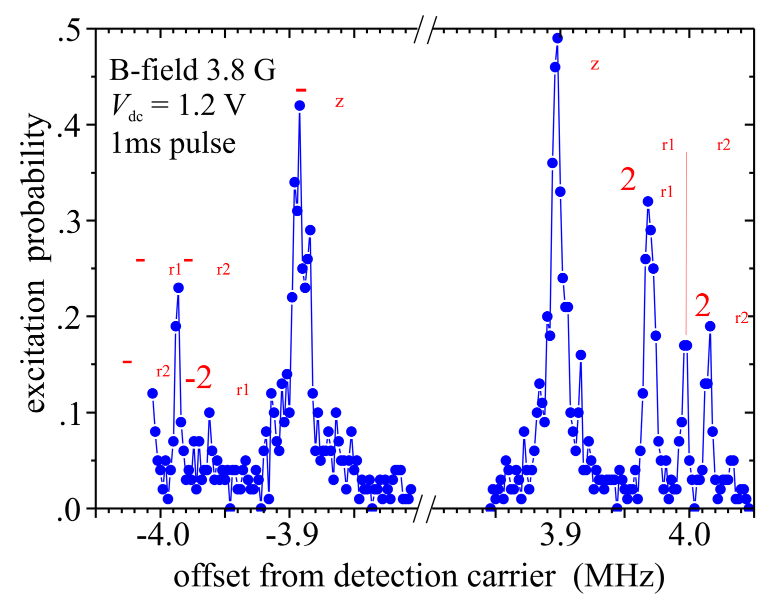

3d micromotion detection

| beam # | x | y | z |
|---|---|---|---|
| 1 | -0.87 | -0.47 | -0.13 |
| 2 | 0.87 | -0.34 | 0.34 |
| 3 | -0.87 | 0.13 | 0.47 |

## Doppler Cooled spectra




2nd harmonics of $_{r1,2}$ overlap with $_z$
some excitation from laser noise at servo freq.s

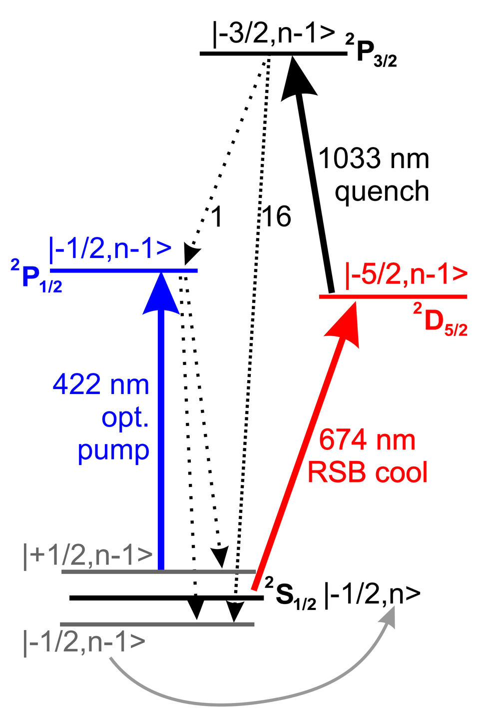



motional sidebands are resolved

axial and 2nd order radial sidebands are separated by applying DC-offset voltage on outer endcap electrode

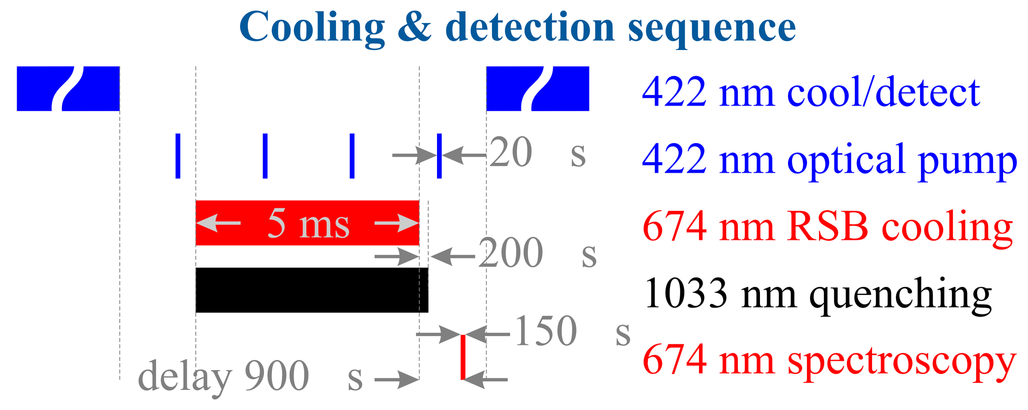
## Zero-point cooling of the axial direction

### RSB-cooling




**Scheme**
- similar to $^{198}Hg^+$[1], $^{40}Ca^+$[3]
- B-field set to 3.8 G
- Doppler cooling to $\langle n_z\rangle = 8$, $\langle n_r\rangle = 14$ [2]
- optical pumping to $^2S_{1/2}$ |-1/2,n> ground state
- 5 ms of RSB cooling on cooling sideband
- 0.9 ms delay for shutters
- spectroscopy on detection sidebands
- 5 ms of state detection
- 7 ms clearout pulse

**Cooling & detection sequence**

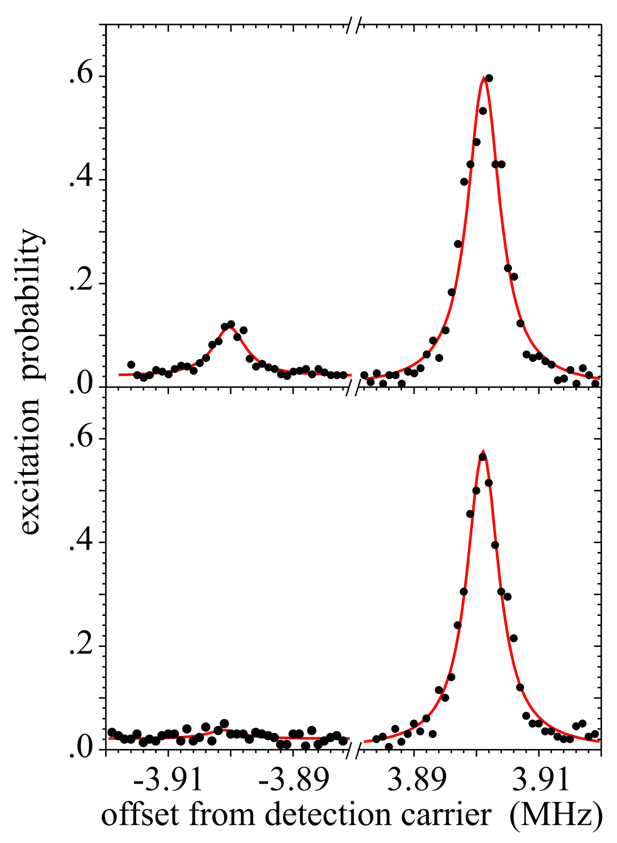



### Determining $\langle n_z\rangle$

- assume thermal distribution of motional states $n_z$
- neglect decoherence during spectroscopy

=> ratio of upper a nd lower detection sideband exc. prob.

$$p_{usb}/p_{lsb} = \langle n_z\rangle/(1+\langle n_z\rangle)$$



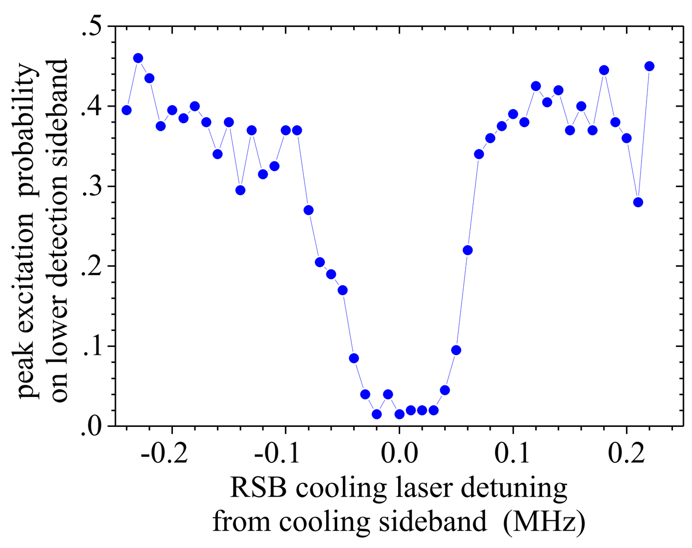

RSB cooling 2 ms
$\langle n_z\rangle = 0.19(2)$

RSB cooling 5 ms
$\langle n_z\rangle = 0.030(12)$

**Dependence on cooling duration**
The optimal RSB cooling duration was found to be 5 ms.

### Adjusting for AC-Stark shift from quencher

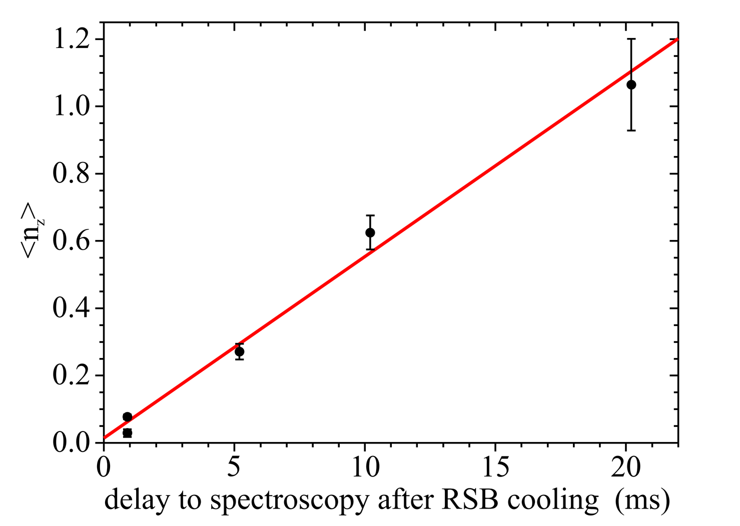
- quench laser detuned by -280 MHz
- cooling sideband shifted by -600 kHz




- spectroscopy laser parked on lower detection sideband
- RSB cooling laser scanned

=> optimum cooling frequency

### Heating rate




linear fit =>
heating rate:
$d\langle n_z\rangle/dt = 0.054(4)$/ms
extrapolating to zero delay:
$\langle n_z\rangle(0\text{ ms}) = 0.014(8)$.

shutters limit minimum measurable $\langle n_z\rangle$

## Conclusions

1) Heating rate 0.054(4)/ms measured due to
- improved electrode surface quality,
- use of photo-ionisation for trap loading [4],
- heating rate compares well with values found in other quadrupole traps [5].

2) RSB cooling to zero-point of motion
- optimum cooling duration 5 ms,
- demonstrated $\langle n_z\rangle = 0.030(12)$ @ 0.9 ms delay,
- extrapolate to min. $\langle n_z\rangle = 0.014(8)$ @ 0 ms.

3) Limitations to the experiment due to
- slow mechanical shutters,
- frequency control of 674 nm laser (stability, agility).

## Outlook

Aim to achieve entanglement of multiple ions for Heisenberg limited stability, e.g. for use in optical clocks and for quantum information processing experiments.
First steps forward are
- migration to linear microtraps for multiple ions/traps [6]
- improve spectroscopy laser stability (Notcutt-style low vibrational sensitivity cavity [7]),
- improved RF frequency agility and laser pulse control (use of FPGAs and DDS, etc.).

## References

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